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ESMGFZ PRODUCTS FOR EARTH ROTATION PREDICTION

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ABSTRACT. The Earth System Modelling Group of GeoForschungsZentrum Potsdam (ESMGFZ) provides geodetic products for gravity variations, Earth rotation excitations, and Earth surface deformations related to mass redistributions and mass loads in the atmosphere, ocean, and terrestrial water storage. Earth rotation excitation compiled as effective angular momentum (EAM) functions for each Earth subsystem (atmosphere, ocean, continental hydrology) are important for Earth rotation prediction. Especially the 6-day forecasts extending the model analysis runs offer essential information for the improvement of ultra-short-term Earth rotation predictions. In addition to the individual effective angular momentum function of each subsystem, ESMGFZ calculates a combined EAM prediction product. Adjusted to the official Earth orientation parameter (EOP) products IERS 14C04 and Bulletin A, this EAM prediction product allows to extrapolate the polar motion and Length-of-Day parameter time series for 90 days into the future via the Liouville equation. ESMGFZ submits such an EOP prediction to the 2nd EOPPCC campaign.

Keywords: Effective Angular Momentum, ESMGFZ, Earth Rotation Prediction, Polar Motion, Length-of-Day

1. ESMGFZ MODELS

The Earth System Modelling Group of GeoForschungsZentrum Potsdam (ESMGFZ) operates on a routine basis the general ocean circulation model MPIOM (Jungclaus et al., 2013) and the hydrological model LSDM (Dill, 2008), both consistently forced with 3-hourly operational atmospheric data from the European Centre for Medium Weather Forecast (ECMWF). In addition to this daily model state updates, ESMGFZ runs daily forecasts for 6 days into the future. From the model states ESMGFZ extracts atmospheric surface pressure, 3D atmospheric winds, ocean bottom pressure, ocean currents, terrestrial water storage, and continental water flows. In order to ensure the global mass balance, the excess water mass from atmosphere and terrestrial water storage is distributed over the ocean considering loading and self-attraction via the sea level equation.

1.1. Atmospheric Surface Pressure and Wind

The operational ECMWF model is typically updated about twice a year. In order to steadily improve the daily weather forecasting quality the numerical scheme, the physical model or the data assimilation procedures are under continuous development. Change in the model scheme, in the background models or in the assimilated variables often introduce offsets in meteorological quantities like atmospheric surface pressure. In consequence, long-term stability in the operational ECMWF deterministic model is not ensured, but the operational model output is the only data that is available in near real-time. Atmospheric pressure decreases with altitude. As a rule of thumb, surface pressure at mean sea level changes by 1 hPa – which approximately corresponds to 1 cm equivalent water height – every 8 m. Thus, atmospheric surface pressure from different numerical models need to refer to the same geopotential height before comparison or even combination into a single time series. ESMGFZ uses a harmonization approach (Dobslaw et al., 2016) to use the latest data from the operational ECMWF deterministic model and simultaneously maintain at the same time the long-term stability of re-analysis data sets.The surface pressure time series from ECMWF reanalysis ERA-40, ERA-Interim, and operational ECMWF were projected onto a time-invariant reference topography under consideration of the time-variable atmospheric density structure.

Analysis data is assumed to be the most precise representation of the state of the atmosphere, but it is typically disseminated every 6 hours only. In order to derive ESMGFZ atmospheric products at higher temporal resolution, we make use of short-term forecasts that are available with 3-hourly sampling from the re-analyses, and even at hourly time step for the most recent years of the operational ECMWF forecasts.

Furthermore, the atmospheric tides were removed by harmonic analysis of 12 major tidal constituents (S1, S2, S3, and M2 frequencies and their modulations), separately for the atmospheric wind and pressure components.

In order to represent the atmospheric and an oceanic contribution in global bottom pressure over the ocean separately, we have to consider the reaction of the sea surface to changes in atmospheric surface pressure. As evidenced from the analysis of global sea-level variations observed with satellite altimetry, the ocean is adjusting almost perfectly to surface pressure changes at periods of a few days and longer. Thus, atmospheric and oceanic contributions to ocean-bottom pressure are highly anti-correlated, and largely cancel out each other when added. To remove the correlation between atmospheric and oceanic contributions in ocean bottom pressure, we only include the static contribution from atmosphere to ocean bottom pressure into the atmospheric surface pressure. Technically, this implies replacing the surface pressure at every grid point over the oceans with the area-mean surface pressure averaged over the whole ocean domain, also known as inverted-barometer (IB) correction. The total mass of the atmosphere is not affected by this operation, but the temporal variability and its anti-correlation with ocean bottom pressure from an ocean model with atmospheric surface pressure forcing reduces substantially.

Finally, a long-term mean atmospheric surface pressure averaged over the period 2003–2014 is subtracted to arrive at pressure anomalies.

1.2. Ocean Bottom Pressure and Currents

Oceanic mass variations are based on a numerical simulation with the Max-Planck-Institute Ocean Model (MPIOM; Jungclaus et al. 2013). We employ code revision #3944 of MPIOM that was released in October 2015 with changes to activate atmospheric surface pressure forcing and a modified vertical momentum transfer in response to surface winds. MPIOM is consistently forced by the ECMWF atmospheric data used for the calculation of atmospheric surface pressure and winds.

As usual, luni-solar gravitational tides in the oceans are not simulated, but tidal waves in response to periodically varying atmospheric pressure loading and surface winds are part of the simulated ocean bottom pressure field. Those signals are removed by harmonic analysis of 12 major tidal constituents (S1, S2, S3, and M2 frequencies and their modulations), separately for the oceanic current and bottom pressure components.

In order to separate the oceanic contribution to ocean bottom pressure, the atmospheric surface pressure applied as a forcing dataset is subtracted. Pressure anomalies are inverse-barometrically corrected by re-adding the difference between the local pressure and the mean pressure averaged over the whole ocean domain. In order to finally remove any fluctuations in total ocean mass induced by the Boussinesq approximation employed in the ocean model momentum equations, the mean bottom pressure averaged over the whole ocean domain is removed by subtracting a homogeneous shell of mass at every time-step (Greatbatch, 1994).

Finally, a long-term mean ocean bottom pressure averaged over the period 2003–2014 is subtracted to arrive at pressure anomalies.

1.3. Terrestrial Water Storage and Riverflow

Terrestrial water storage and flows are simulated with the Land Surface Discharge Model (LSDM; Dill, 2008). Physics and parametrisation of LSDM include the representation of soil moisture, shallow groundwater, snow coverage, and surface water stored in rivers and lakes. The horizontal water transport is realized by surface runoff, wetland runoff, river flow, and drainage in the groundwater compartment. LSDM is driven by daily 2m-temperatures, precipitation, and evaporation from the harmonized ECMWF atmospheric data.

Finally, a long-term mean terrestrial water storage averaged over the period 2003–2014 is subtracted to arrive at water storage anomalies.

1.4. Barystatic Sea Level

The global water budget is not closed in our model sets, since atmospheric fluxes such as precipitation and evaporation are not part of the atmospheric analyses calculated at ECMWF, but instead are taken from high-resolution deterministic forecast model runs initialized from the analyses only. The consideration of the global mass balance effects is, however, particularly important for seasonal variations, e.g. in the Length-of-Day. We therefore assume that the total mass in atmosphere, oceans, and all land storages should be constant at any given time. Potential missing mass is assumed to be stored in the oceans only. Any net-inflow of water masses into the oceans will cause a barystatic increase in ocean mass. The actual geographic position of that inflow is not important, since pressure gradients imposed at the surface of the ocean by an inflow of water will trigger barotropic gravity waves that effectively adjust the global sea level almost instantaneously. To account for the global mass balance, we integrate all atmospheric and terrestrial masses as represented by LSDM and ECMWF over the whole globe at any time-step. Global masses simulated by MPIOM reflecting ocean circulation dynamics are constant as enforced after correcting for effects of the Boussinesq approximation. We consider a spatially variable relative sea level pattern due to the effects of self-attraction and loading by solving the sea-level equation (Tamisiea et al, 2010).

2. ESMGFZ PRODUCTS

All ESMGFZ products are derived from one consistent basis of daily updated operational ECMWF atmospheric data, simulation with the ocean model MPIOM, the hydrological model LSDM barystatic sea level variations from the model global mass balance. All products start in the year 1978 and are updated daily at about 11 UTC for the time steps of the last day. Daily updates include also 6-day forecast runs for all products. ESMGFZ products are accessible via the GFZ webpage www.gfz-potsdam.de/en/esmdata, see Fig 1.

Figure 1. ESMGFZ Products homepage, www.gfz-potsdam.de/en/esmdata

2.1. GRACE De-aliasing Product, AOD1B

Non-tidal high-frequency atmospheric and oceanic mass variation models are provided as so-called Atmosphere and Ocean De-aliasing Level-1B (AOD1B) products. They are added to the background static gravity model during GRACE monthly gravity field determination. AOD1B products are 3-hourly series of spherical harmonic coefficients up to degree and order 180 which are routinely provided to the GRACE Science Data System and the user community with only a few days time delay. The GRACE AOD1B products were accepted by the International Earth Rotation and Reference Systems Service (IERS) Global Geophysical Fluid Center (GGFC) as Provisionary Products in 2009 and have been given the status of GGFC Operational Products in May 2012 (Dobslaw et al., 2017).

2.2. Non-tidal Elastic Surface Load Deformation, NTAL, NTOL, HYDL, SLEL

Elastic surface deformations are calculated in the spatial domain by convolving loading Green's function with simulated mass distributions from ECMWF atmospheric surface pressure, MPIOM ocean bottom pressure, LSDM terrestrial water storage, and global mass balance barystatic sea level variations. Spatial calculation is performed on a 0.125° global grid in the near-field ($\leq$3.5°) and on a 2.0° grid in the far-field (>3.5°) (see Dill et al. (2015) for more details). Gridded loading displacements are stored on a regular 0.5° global grid with 24h sampling for hydrological and sea level loading (HYDL, SLEL) and 3-hourly sampling for nontidal atmospheric and oceanic loading (NTAL, NTOL) according to the time steps of the modeled mass data sets. For each loading component, a 6-day forecast product (NTALF, NTOLF, HYDLF, SLELF) is also available.

2.3. Effective Angular Momentum, EAM

Earth rotation excitations are derived by summarizing the angular momentum changes from mass re-distributions in any of the subsystems atmosphere, ocean, and continental hydrology. The residual effect on the orientation of the solid Earth as represented by the terrestrial reference frame realized through a set of geodetic observatories leads to so-called effective angular momentum time series (EAM), AAM (3h) for atmospheric surface pressure and wind, OAM (3h) for ocean bottom pressure and currents, HAM (24h) for terrestrial water storage and water flows, SLAM (24h) for barystatic sea level variations. EAM data are dimensionless time series of the matter and motion terms, each with two components for polar motion excitation and one component for Length-of-Day variations. The efficacy of mass re-distribution in the global geophysical fluid layers at the Earth surface is governed by the Earth's actual rheology. This includes in particular the elastic deformability of the Earth in response to surface loads and effects of a partly de-coupled rotation of the Earth's core.

A long-term temporal mean was subtracted from all EAM components as estimated over the time-period 2003 – 2014 that approximately matches the length of one full solar cycle. For more details, please read the Product Description Document http://esmdata.gfz-potsdam.de:8080/repository/entry/show/Home/Effective+Angular+Momentum/Documents/Product+Description+Document.

2.4. Earth Rotation Prediction, EAMP, EOPP

ESMGFZ provides not only daily updated effective angular momentum function for Earth rotation excitation but also 6-day forecasts (EAMF) for each of the subsystems. ECMWF atmospheric forcing data shows reasonable prediction skill for about 5 days into the future. As model-based EAM data is able to represent 80–90% of the geodetically observed Earth rotation excitation in the period range from days to years, EAMF forecasts based on MPIOM and LSDM model runs forced with ECMWF atmospheric forecasts can provide essential information on short-term Earth rotation variations that are not available from any other geodetic data products. Introducing EAMF forecasts into classical Earth orientation parameter (EOP) predictions can significantly reduce the short-term EOP prediction error.

In addition, to the 6-day EAMF forecast, ESMGFZ provides a 90-day EAMP prediction product. This product is calculated as a combination of EAM analysis data, geodetic angular momentum derived from the official IERS 14C04 EOP time series, rapid EOP time series taken from Bulletin A to fill the gap, typically around 30 days, between the last day of 14C04 and today, and 6-day EAMF forecasts. The EAMP product contains EAM data for the last 90 days and a prediction part 90 days into the future with 3-hourly sampling.

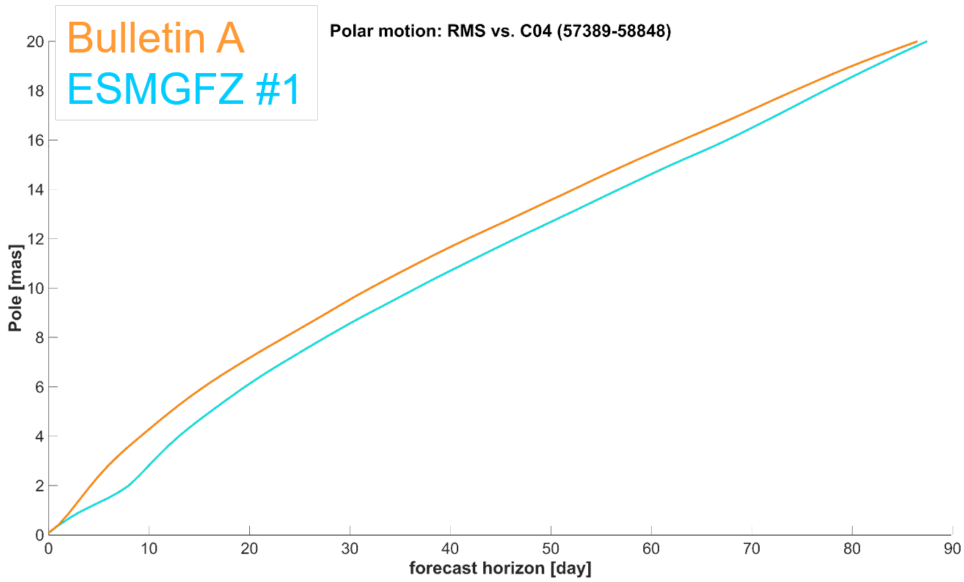

Figure 2. RMS error of polar motion prediction compared to IERS 14C04 of Bulletin A (orange) using no EAMF data and ESMGFZ submissions #1 to EOPPCC (blue) using the ESMGFZ EAMP product

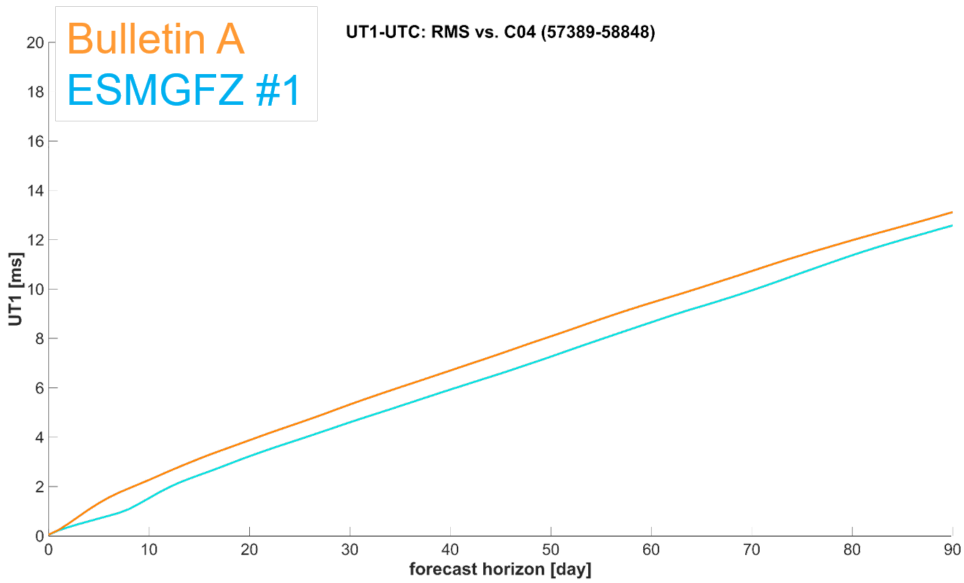

Figure 3. RMS error of UT1−UTC prediction compared to IERS 14C04 of Bulletin A (orange) using no EAMF data and ESMGFZ submissions #1 to EOPPCC (blue) using the ESMGFZ EAMP product

The EAMP product is the basis for our EOPP prediction submitted to the 2nd EOP prediction comparison campaign (EOPPCC). We take the latest available set of EOP estimates from USNO, made available in Bulletin A via CDDIS, as initial values and integrate our 90-day EAMP prediction forward in time to obtain a 90-day EOPP prediction for polar motion, UT1−UTC, and dLOD.

Figs. 2 and 3 show the reduced RMS forecast error for ultra-short-term predictions due to the additional introduction of EAMF 6-day forecasts into EOP prediction. Moreover, the 6-day EAMF forecasts could also improve the EOP predictions for lead times longer than 6-days.

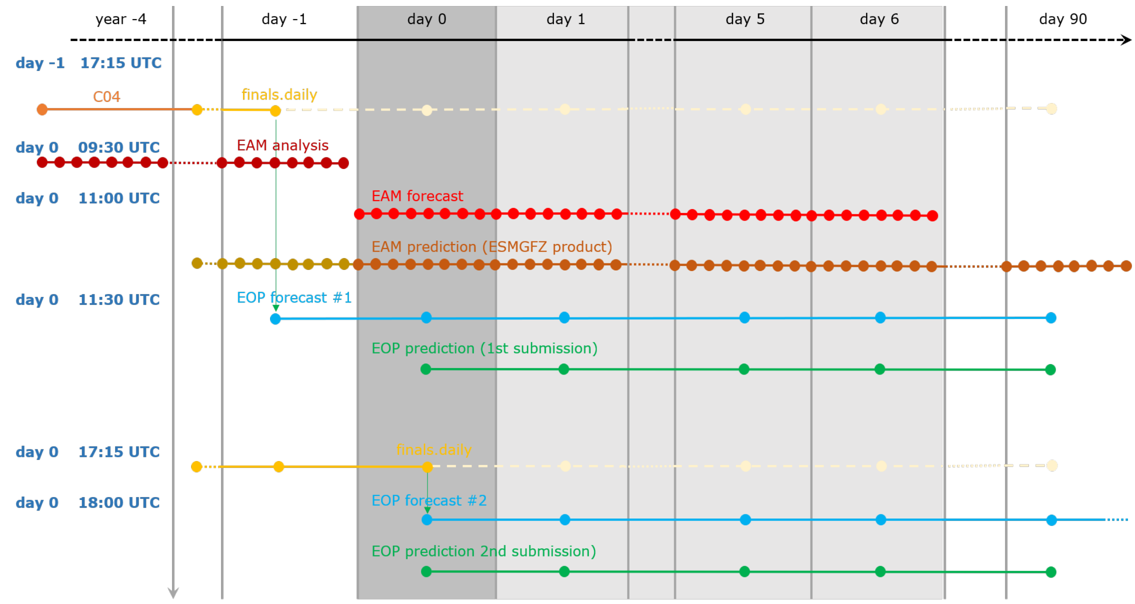

Figure 4. Two submissions to EOPPCC using the same EAMP product (brown) but different initial values from Bulletin A

In order to discuss the impact of the accuracy of the initial value, we prepare two submissions. The first submission is calculated around 11 UTC as soon as the EAMP prediction is available (Fig. 4). At that time the latest Bulletin A is from the day before meaning that the latest initial value in Bulletin A that is not predicted is from the day before. We calculate our EOP prediction using the latest EAMP product that starts also at the day before. Therefore, ESMGFZ EOP prediction starts with the current day as the first predicted day. Later in the evening, we calculate our second submission when the updated Bulletin A values for the current day are available. The second submission uses the same EAMP product as the first submission, starting 1 day later. Comparing our two submissions in the 2nd EOPPCC will give more insights into the influence of an updated initial value.

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